A Review of Subsidence Measurements near Mendota, California

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ABSTRACT

The image of Dr. Poland of the United States Geological Survey (USGS) standing next to a marked powerline in 1977 is circulated as a striking example of land subsidence. This and other historical data are common references for modern subsidence studies. Because of the significance of this data, recent work was conducted to analyze the historical data as well as independently measure the magnitude of subsidence since 1975, within the same study area southwest of Mendota, CA. The results indicate that local subsidence in the area of the photo is less than 0.5 meters between 1975 and 2017. Furthermore the results identify inconsistencies that may challenge the historical certainty of some local subsidence data. Procedures and methods used in the survey will also be discussed.

INTRODUCTION

There is an existing famous image of Dr. Poland (of the United States Geological Service) standing next to a power pole in the San Joaquin valley. The image is intended to depict the magnitude of subsidence in the area. This work evaluated historical data to review the reasonableness of the famous image as well as new, independent surveys to measure subsidence since the image was taken. It is important to note that this work represents a cursory, incomplete evaluation. Some historical data remains inaccessible, such as historic published elevations of a few local benchmarks. However, continuing efforts are focused on accessing and analyzing the missing data.

The review consisted of two tasks:

1. Using satellite observations to determine approximate heights of local benchmarks
2. Compare historic values of those and other benchmarks in the area.

The correct term for vertical values (elevations) used in this review is orthometric height, which the height on the surface above the geoid. The surface of the geoid varies on which vertical datum that is used, which is either National Geodetic Vertical Datum of 1929 (NGVD29) or the North American Vertical Datum of 1988 (NAVD88). The horizontal positions shown in this review are based on North American Datum of 1983 (NAD83) using the 2011 realization.

Horizontal positions are on the State Plane projection, California Zone 4 and the units for those positions, as well as orthometric heights are meters.

FIELD WORK

The field work was done on June 13, 2017 by Dr. Stuart Styles and Mr. Tom Mastin. The field work consisted of doing some RTK survey procedures and some static procedures using NavCom LandPak system consisting of two SF-3040 receivers and appropriate accessories including a Nautiz X7 controller. In addition a Leica TCR805 total station was used to measure the height of a power pole.

One of the SF-3040 receivers was set over a spike along the California Aqueduct which was used as a base station, collecting data continuously while the field work was being performed. The other unit was used as a rover. Most of the benchmarks measured were done so that a rapid static solution could be determined. A minimum of twenty minutes was collected at each rapid static site. 5 benchmarks were located, two near the site, but off the aqueduct, one along the aqueduct, one east of the Dr. Poland site, but in the valley, and one west of the pole and outside of the valley. The rapid static process requires post processing in order to determine positions.

A few points were collected using RTK process, which only required 3 seconds, but did not allow for post processing. These were some benchmarks near the base station, along the aqueduct, as well as the elevation of the water within the aqueduct.

A power pole near the original pole that was in the Dr. Poland image was measured for height. An elevation was calculated at the base (which was not definitive), at a spike set about 2 meters above the ground, at the top of the wooden pole and at the top of the top insulator.

ESTABLISHING POSITIONS BASED ON STATIC AND RAPID STATIC SURVEY

The positions were first processed through the National Geodetic Survey (NGS) On-line Positioning User Service (OPUS). This service can do both static (2 hours or more data) or rapid-static (15 minutes to 2 hours of data), providing positioning and precision information. This process uses Continuously Operating Reference Station (CORS) sites to determine the position. In selecting the CORS stations, the service will reject CORS stations that are low precision relative to other selected stations. Currently OPUS only uses GPS satellites in its solution.

The static process uses 3 CORS stations and performs three independent single baseline solutions. The base station went through the static process and had an overall:

1. RMS of 0.012m,
2. Peak-to-peak error of 0.012m for the horizontal solution
3. Orthometric height error of 0.027m, of which 0.018m is caused by using a geoid model (Geoid12B model) to determine the orthometric height.

The Rapid static process will use up to 9 CORS stations, and was performed on 6 sites with all but one resulted in good statistical solutions. One site (Point # 2003, benchmark Y 1258) had one very low but acceptable quality indicator. All had a normalized RMS (unitless) of less than 1, which is expected. In reviewing the CORS sites selected, it was clear that no CORS sites were used within the valley, which meant that some of the CORS stations being used were quite a distance from the site (Up to 130km away).

Due to the distance and because OPUS only uses GPS satellites for its solution, a decision was made to use the Post Processing software “GNSS Solutions” from Spectra Precision to process all the data. In addition the three nearest CORS stations that surrounded the site were selected to provide a stronger network. They were not used as controlling positions, but used to weigh the vector solutions. The position of the base station (Point #2000) based on the static OPUS solution was used as control, creating a minimally constrained solution (constrained at only one point). Table 1 shows the results of this process, along with the variation between this solution and the OPUS rapid static solution. It can be noted that #2003 has a large variation in the orthometric height, which is possibly due to the poor solution using OPUS-RS.

Table 1. Data comparison to OPUS

Point ID	Northing m	Easting m	Ortho Ht m	Description	PID	Δ North	Δ East	Δ Ortho Ht.
2000	649,717.68	1,862,587.13	103.36	Set Spike on Aquaduct		0.000	0.000	0.000
2001	649,744.15	1,862,605.52	98.19	BM Z 1444	GU4142	-0.007	0.008	-0.009
2003	649,804.58	1,862,893.45	96.79	BM Y 1258	GU0100	0.002	0.020	0.106
2004	650,384.78	1,864,071.65	90.44	Set Spike by Pole		0.001	0.005	0.032
2005	644,498.41	1,851,619.70	188.77	BM F 928		-0.005	-0.005	0.007
2006	650,546.78	1,862,149.58	102.71	BM S 1194		-0.010	0.000	0.008
2007	656,469.55	1,868,030.81	70.62	BM J 998	GU0814	-0.008	-0.006	0.020
P301	664,853.25	1,844,473.53	123.17	CORS Station				
P302	645,623.83	1,855,258.40	156.63	CORS Station				
P304	656,830.90	1,878,847.65	50.99	CORS Station				

Once the positions were determined to be acceptable, the data from an RTK survey and the pole heights from the total station survey were added to the coordinate list. Table 2 shows the final values for the positions within the site.

Table 2. Final coordinates from field survey

Point ID	Northing m	Easting m	Ortho Ht. m	Description	Method
2000	649,717.68	1,862,587.13	103.36	Set Spike on Aquaduct	Static
2001	649,744.15	1,862,605.52	98.19	BM Z 1444	Rapid Static
2003	649,804.58	1,862,893.45	96.79	BM Y 1258	Rapid Static
2004	650,384.78	1,864,071.65	90.44	Set Spike by Pole	Rapid Static
2005	644,498.41	1,851,619.70	188.77	BM F 928	Rapid Static
2006	650,546.78	1,862,149.58	102.71	BM S 1194	Rapid Static
2007	656,469.55	1,868,030.81	70.62	BM J 998	Rapid Static
2008	649,672.49	1,862,598.71	104.83	BM L 111.91	RTK
2009	649,651.99	1,862,617.74	104.36	Aqua 1 Reference Mark	RTK
2010	649,635.59	1,862,614.12	102.67	L111.93	RTK
2011	649,636.40	1,862,606.02	99.83	Water Level	RTK
2020	650,360.67	1,864,028.28	90.68	Ground at Pole	T. S from Pt 2004
2021	650,360.67	1,864,028.28	92.34	Spike at Pole	T. S from Pt 2004
2022	650,360.67	1,864,028.28	106.11	Top wood pole	T. S from Pt 2004
2023	650,360.67	1,864,028.28	107.38	Top of Insulator	T. S from Pt 2004

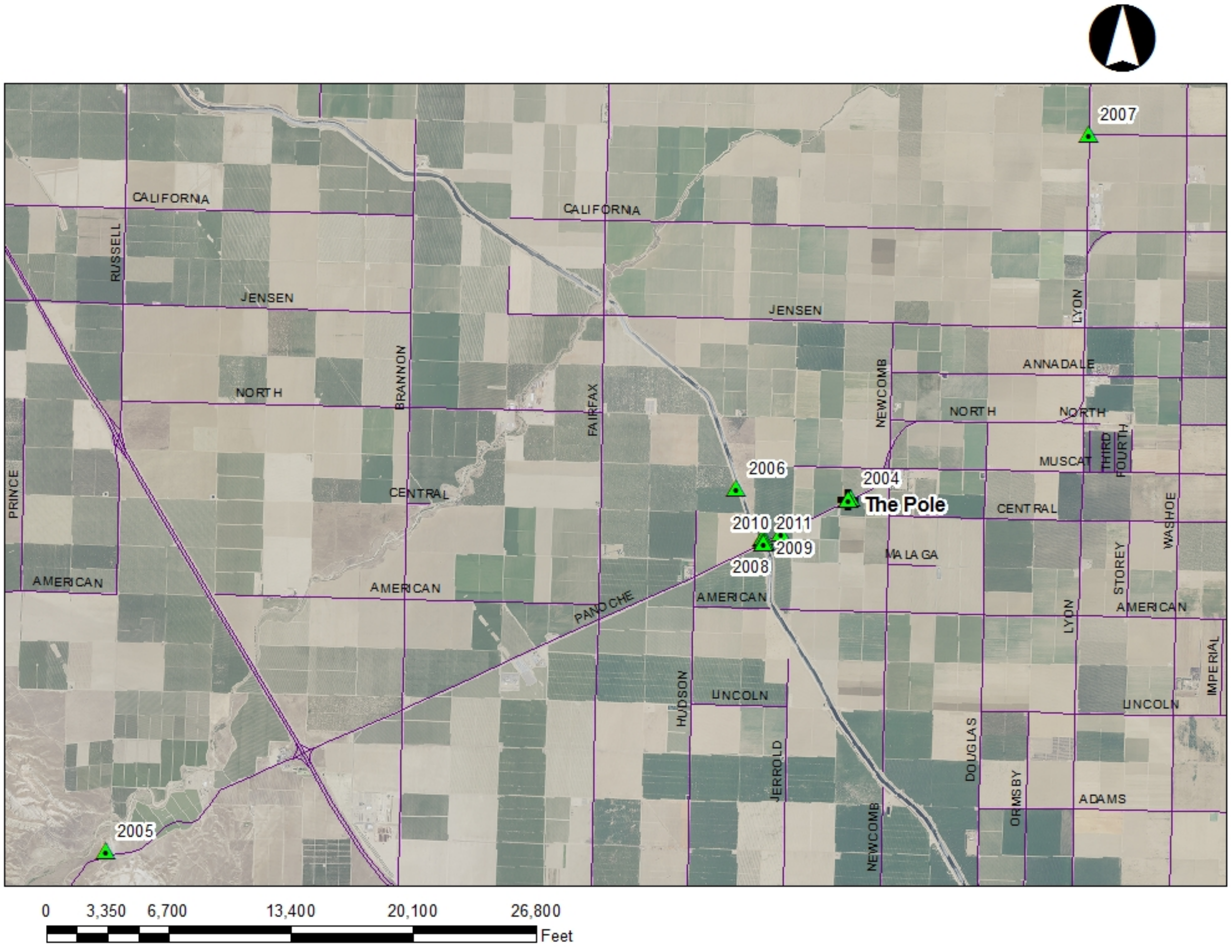

Figure 1. Benchmark and telephone pole location map; Interstate 5 freeway is shown running north-west along the left side of the map

REVIEW OF NGS LEVEL RUNS

NGS provided a number of files dealing with level loops that had been done the area of Mendota. The primary files used were the “P” files which showed the level run unadjusted elevations. These were the only files used as a part of this review

The “P” files were brought into Excel and then a summary was created showing each benchmark with what loops they were measured on and what that measured elevation was. These elevations are on NGVD29 datum. In addition each benchmark had an approximate position using latitude and longitude coordinates, and appear to be on NAD27 datum.

There were 12 level loops provided with approximately 1136 unique benchmarks between the 12 loops. 112 benchmarks were measured on at least 2 level loops. Each benchmark is identified by their permanent Identification (PID) and their designation.

Table 3. Summary of level lines from NGS

Line #	Start Date	End Date	BM Count
L10298	12/28/1942	1/13/1943	94
L12105	2/7/1947	3/26/1947	180
L14749	2/24/1953	2/24/1953	74
L15764/7	9/7/1955	9/12/1955	42
L16526/7	12/10/1957	12/12/1957	37
L17723/7	11/16/1959	12/14/1959	48
L19091/7	2/18/1963	2/25/1963	72
L20029/1	9/24/1964	12/21/1964	569
L20605/6	1/26/1966	1/28/1966	42
L21703/13	12/13/1968	2/4/1969	34
L22671/5	2/3/1972	2/7/1972	34
L23760	1/27/1975	3/24/1975	333

The first comparison was with the measured benchmarks as described before. The datasheets for each benchmark were obtained through NGS at https://www.ngs.noaa.gov/datasheets/index.shtml for all the surveyed benchmarks. Most of the benchmarks had a current orthometric height based on NAVD88 and a superseded orthometric height for NGVD29.

In Table 4 the calculated NGVD29 elevations are based on using the Vertcon program from NGS which calculates the difference from NGVD29 to NAVD88, based on the location and then apple that correction to the measured Orthometric height. This calculation is approximate only. The Published date for NGVD29 are all listed as 1992. These published values for the most part do not match any of the level lines that NGS provided, but are for the most part within 0.1’ of the elevations on the 1975 level line. The date on the NAVD88 are based on the date shown on the data sheets for that elevation. Point 2001 had no NGVD29 elevation as it was set in 1989. Point 2009 does not show up any more on the NGS data sheets, but the data provided from NGS had elevation for that point. It is of interest to note that Point 2005, which has only a small variation between measured and published, was the one benchmark out of the valley.

Table 4. Comparison of measured benchmarks to published values

Point ID	NGS PID	Designation	Ortho Ht. m Measured	NAVD88 m Published	Meas. - Publ.	Date of NAVD88	NGVD29 m Calculated	NGVD29 m Published	Calc. - Publ.
2001	GU4142	Z 1444	98.190	98.420	-0.230	2010			
2003	GU0100	Y 1258	96.787	97.155	-0.369	1986	96.008	96.430	-0.422
2005	GU0588	F 928	188.772	188.763	0.009	2011	187.889	187.870	0.019
2006	GU0046	S 1194	102.712	103.138	-0.426	1986	101.929	102.410	-0.481
2007	GU0814	J 998	70.623	71.049	-0.426	1986	69.879	70.299	-0.421
2008	GU0044	L 111.91	104.832	105.202	-0.370	1986	104.052	104.446	-0.394
2009	GU0040	Aqua 1 RM	104.358				103.578	104.059	-0.481
2010	GU0039	L 111.93	102.673	103.114	-0.441	1986	101.893	102.331	-0.438

Table 4 would at least initially indicate that the change in elevation over the last 20 years is a little under 0.5 m. This is a small sample set, but does give a fairly consistent change in elevation.

Of the benchmarks located, all but Point 2001 had been a part of at least one of the level runs provided by NGS. Table 5 shows the values for each of the located benchmarks, for the level line runs that they were a part of. Again the NGVD29 calculated values are based on the NAVD88 measured values with the correction based on VERTCON being applied.

Table 5. Level line values for located benchmarks

			NGVD29	Level Line Runs			
Point ID	NGS PID	Designation	Calculated	L20605/6	L21703/13	L22671/5	L23760
2003	GU0100	Y 1258	96.008				96.379
2005	GU0588	F 928	187.889				187.955
2006	GU0046	S 1194	101.929				102.382
2007	GU0814	J 998	69.879	70.814	70.215	70.291	
2008	GU0044	L 111.91	104.052		104.447	104.446	104.432
2009	GU0040	Aqua 1 RM	103.578				104.007
2010	GU0039	L 111.93	101.893		102.331	102.331	102.318

The next consideration was to look at some of the benchmarks that had been used on more than one level line. The criteria was that the benchmark was a part of the oldest level line of the data set and then it was measured on at least 4 level lines. Two benchmarks (PID GU0119 and GU0120) were removed as they were not surveyed between 1955 and 1975.

Table 6 shows the maximum change in elevation to be 6.804 m and the minimum over that time to be 3.940 m.

Table 6. Selected benchmarks to compare

		L10298	L12105	L14749	L15764/7	L16526/7	L17723/7	L19091/7	L20029/1	L20605/6	L21703/13	L22671/5	L23760	Change in
PID	Designation	Jan 1943	Mar 1947	Feb 1953	Sep 1955	Dec 1957	Dec 1959	Feb 1963	Dec 1964	Jan 1966	Feb 1969	Feb 1972	Mar 1975	Elevation
GU0092	E 220	120.355	116.719	120.150	119.121	116.496	116.424	116.247	116.351	116.258				4.107
GU0094	R 661	112.801	109.139	112.427	111.256	108.482								4.319
GU0098	GWM 14	105.101	101.435	104.874	103.650	100.835	100.601	100.238	100.226	100.064			99.284	5.818
GU0103	S 661	97.331	93.639	96.702	95.310	92.408	92.127	91.596	91.529	91.343	90.536	90.546	90.527	6.804
GU0797	M 220	54.326	50.529	54.585	54.171	52.046								4.057
GU0799	X 661	53.555	49.802	53.994	53.646	51.540								4.192
GU0800	Y 661	52.476	48.767	53.149	52.859	50.771	51.128							4.381
GU0815	GWM 77 USGS	83.375	79.417	82.376	81.356	78.824	78.768	78.585		78.493	77.839	77.881		5.537
GU0822	J 220	78.079	73.906	77.410	76.620	74.023								4.173
GU0824	V 661	74.970	70.849	74.471	73.687	71.189				71.053				4.120
GU0827	GWM 78 USGS	69.138	65.162	68.994	68.382	66.078				66.333	65.782	65.858		3.975
GU0829	W 661	63.248	59.355	63.295	62.788	60.597								3.940
GU0830	GWM 13 USGS	60.158	56.297	60.268	59.789	57.641								3.971

Level run elevations for Benchmark SW 661 (GU0103) which was the benchmark that Dr. Poland used according to his photo, is shown in Figure 2.

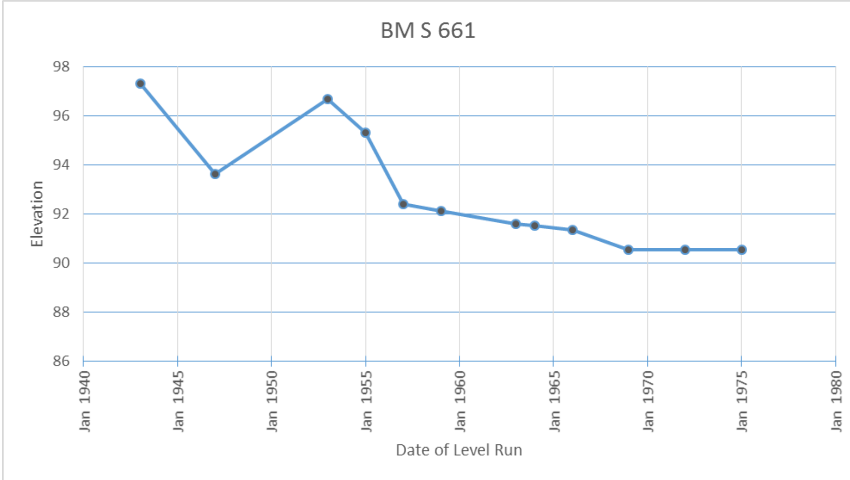

Figure 1. Change of elevation for BM S 661

In reviewing Benchmark S 661 and other benchmarks apparent data anomalies were identified - the benchmark dropped about 3.5 meters between 1943 and 1947, then increased in elevation by about 2.5 meters between 1947 and 1953.

Subsequently, the benchmark subsequently showed more reasonable changes in elevation after 1957. This anomaly shows up on all the other benchmarks listed. Each level run elevations were based on the current elevation of the benchmark from which the run started. So the location of each of the start points was evaluated. The first, third and fourth level run all started on benchmarks outside of the valley, and in the hills west of the valley. While all the other runs started on a benchmark that was in the valley.

A plot showing the change in elevation from January 1943 on the monuments reviewed shows that all had a large drop in elevation from 1943 to 1947, then all had a major rebound in 1953 and then again a large drop in 1957.

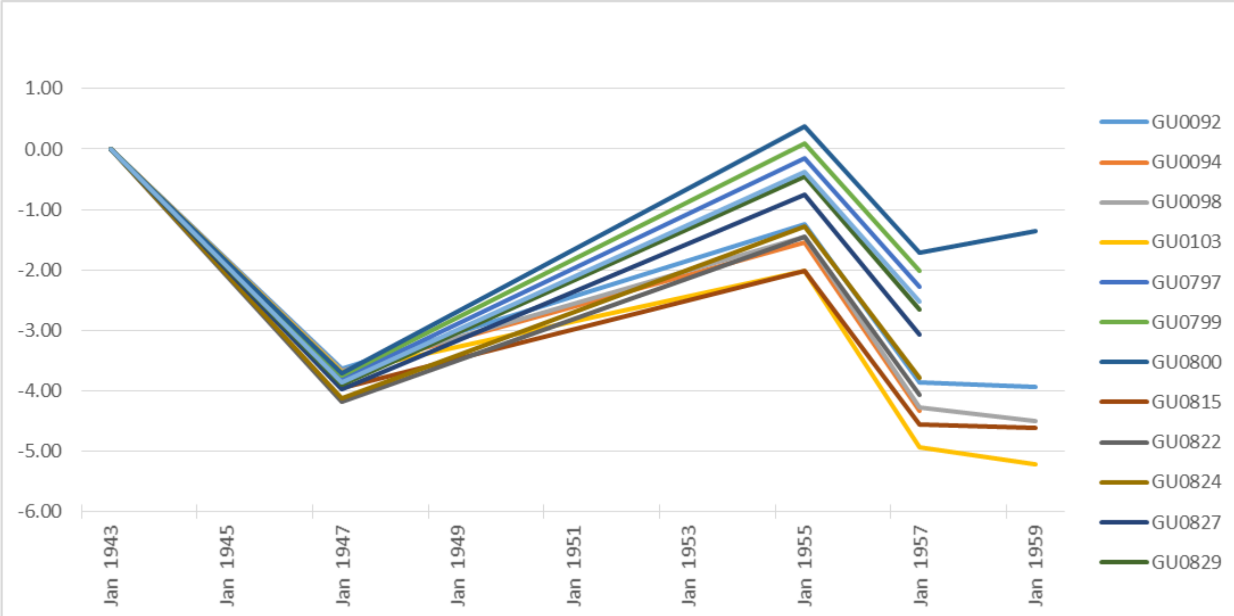

Figure 2. Change in elevation compared to 1943; vertical (y) axis is elevation (in meters)

It seems counterintuitive that the problem would be from the benchmarks lying outside of the valley, but based on the numbers there was a definite variation between runs started in the hills as opposed to those started in the valley. Therefore, the same set of benchmarks were compared after removing the first, third and fourth level run. Table 6 shows that results.

Table 7. Comparison benchmarks with level runs 1, 3 and 4 removed

PID	Designation	L12105 17252	L16526/7 21166	L17723/7 21898	L19091/7 23067	L20029/1 23732	L20605/6 24135	L21703/13 25238	L22671/5 26336	L23760 27477	Change in Elevation
GU0092	E 220	116.719	116.496	116.424	116.247	116.351	116.258				0.471
GU0094	R 661	109.139	108.482								0.657
GU0098	GWM 14	101.435	100.835	100.601	100.238	100.226	100.064			99.284	2.152
GU0103	S 661	93.639	92.408	92.127	91.596	91.529	91.343	90.536	90.546	90.527	3.112
GU0797	M 220	50.529	52.046								1.517
GU0799	X 661	49.802	51.540								1.738
GU0800	Y 661	48.767	50.771	51.128							2.361
GU0815	GWM 77 USGS	79.417	78.824	78.768	78.585		78.493	77.839	77.881		1.578
GU0822	J 220	73.906	74.023								0.118
GU0824	V 661	70.849	71.189				71.053				0.340
GU0827	GWM 78 USGS	65.162	66.078				66.333	65.782	65.858		1.171
GU0829	W 661	59.355	60.597								1.242
GU0830	GWM 13 USGS	56.297	57.641								1.344

By removing those three level runs the maximum change in elevation is 3.112 meters and the minimum is 0.118 meters. In addition, the plot of Benchmark S 661 shows a more consistent rate of subsidence.

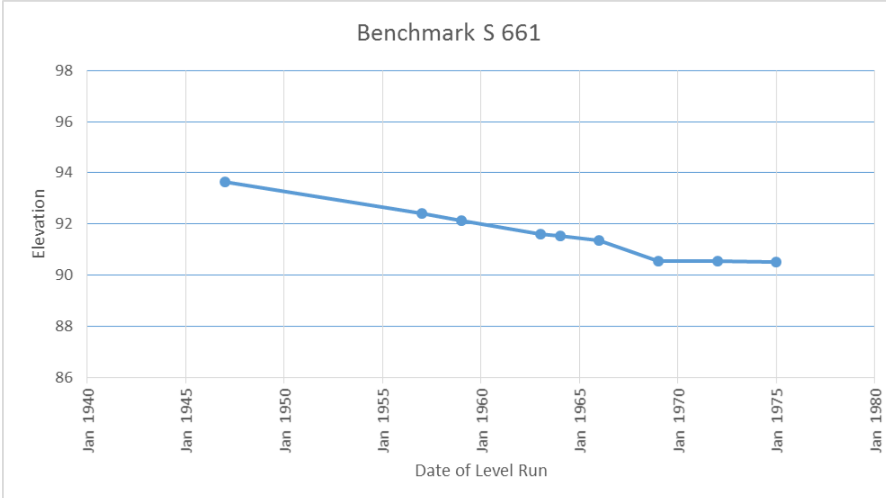

Figure 3. Benchmark S 661 without level run 1, 3 and 4

In an attempt to extrapolate where Benchmark S 661 would be today, the change in elevation at benchmark Y 1258 (PID GU0100) from March 1975 to June 2017 was used. Benchmark Y 1258 was used, as it was the closest benchmark found to the now missing benchmark S 661. It was determined to be about 1.2 km from benchmark S661. The measured value was converted to NGVD29 and then compared to the elevation from January 1975. Note this is basically the same difference between the published NAVD88 value for Y 1258 and the measured value (See table 4).

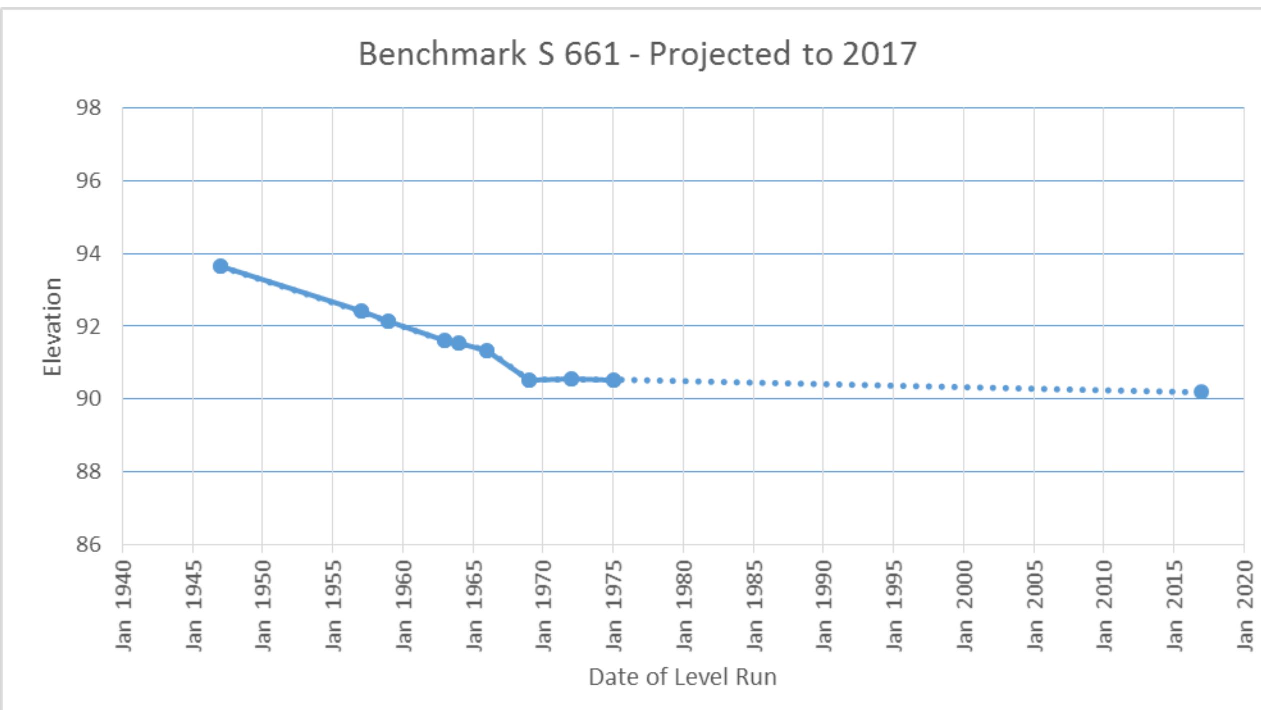

Figure 4. Projected change in elevation for S 661 using Benchmark Y 1258 (NGVD29)

The final portion of the analysis resulted in the creation of a surface model of the changes using all the benchmarks that had multiple measurements. The surface is not the best representation of local subsidence, because not all benchmarks were measured on all of the level runs. This creates some disparity in the surface, however it does tend to show the general areas of maximum change.

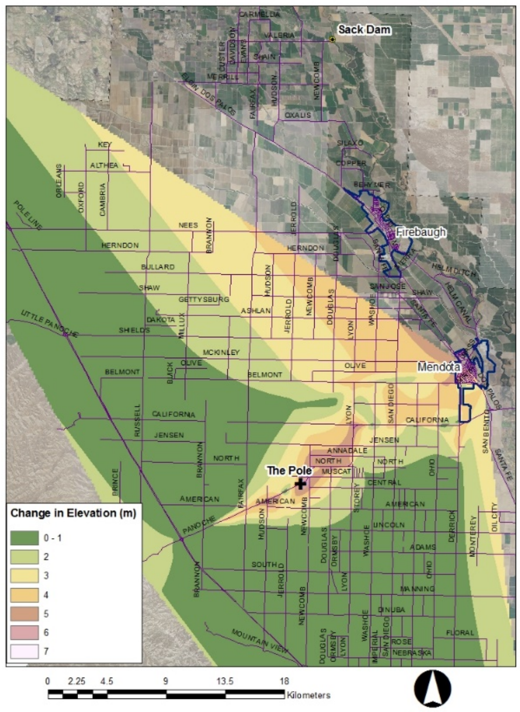

Figure 5. Surface of change using all level run data

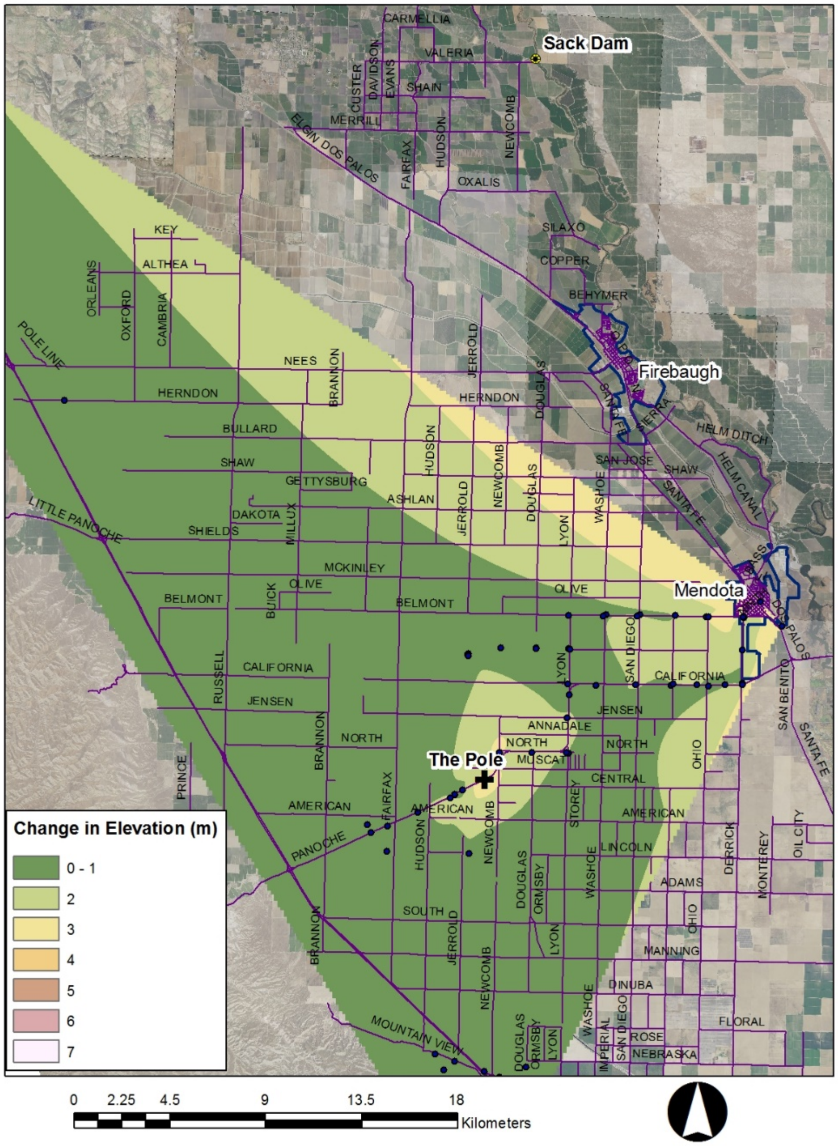

Figure 6. Surface of change without level line 1, 3 and 4

RESULTS

Based on the analysis of accessible data, there is no definitive value of the amount of local subsidence. Information measured in the field was compared to not only the published elevations on the benchmarks, but also to a series of level runs performed by NGS from 1943 until 1975. The runs had unadjusted elevations based on the current elevation of their starting benchmark. Two potential issues have been identified with this approach:

1. The starting benchmark may or may not have subsided since its elevation was determined
2. The level runs did not repeat the same course, despite overlapping benchmarks between all the runs.

In looking at the level runs, it is clear that at least with the information available, it is difficult to determine the precise amount of subsidence. However, there are some general observations that are supported by this review. First there appears that most of local subsidence occurred between 1947 and 1965, specifically in the area of the "pole" and in the area of Mendota.

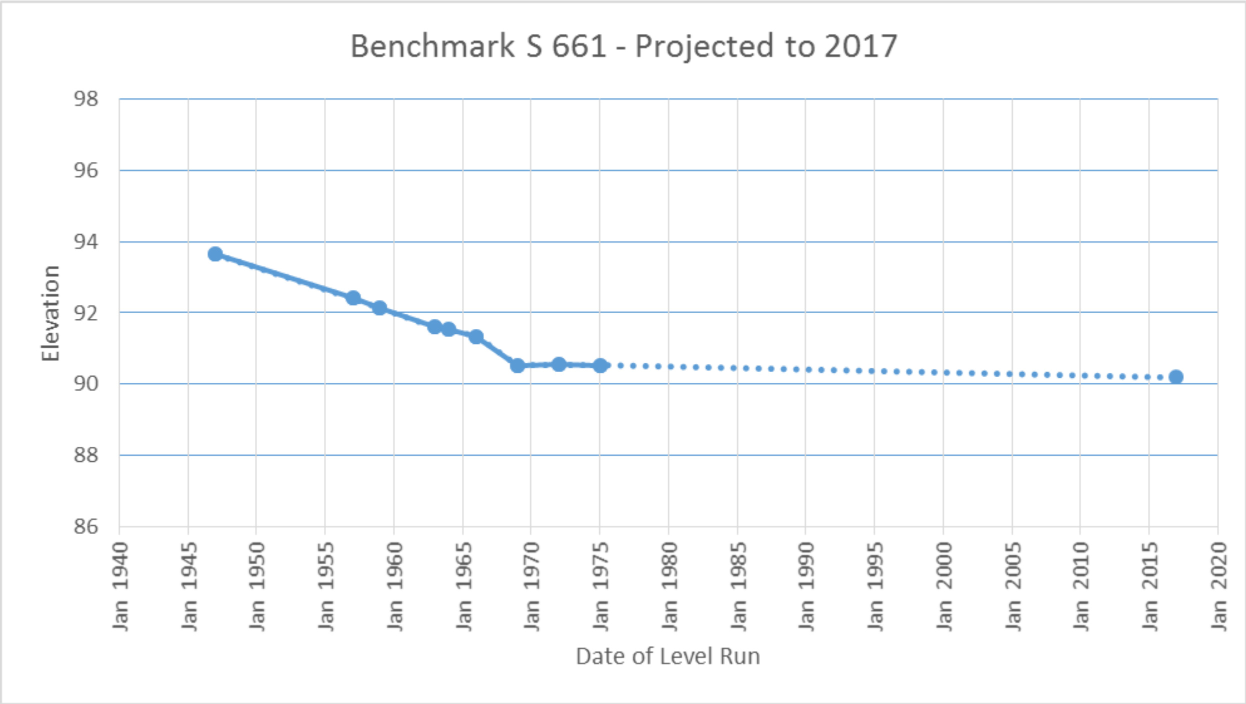

Figure 8. Resulting elevations for Benchmark S 661; elevation in meters

It appears that subsidence slowed significantly around the late 1960's. The benchmark that Dr. Poland used (S 661 PID GU0103) may have subsided as much as 3 meters from 1943 to 1975 with the majority occurring between 1943 and 1957.

In reviewing the level runs, something stood out. From the first run in 1943 to the second run in 1947, there was about a 3.5 meter drop in most elevations. Then from 1947 to 1953 the elevations rebounded most of that 3.5 meters. In reviewing the starting benchmarks, the first, third and fourth run were all based on benchmarks outside of the valley. All the others were based on benchmarks within the valley. When you remove those three runs, the maximum change in elevation from 1947 to 1975 is only about 3 meters. Intuitively, holding benchmarks outside the valley would make sense to measure subsidence. However, the fact that remaining level runs, there is a more consistent change in elevation. There is not enough evidence in this review to quantitatively assert that subsidence in this area over the last 70 years is really only about 3 meters, but this review does question the assertion based on the Dr. Poland photo.

Based on the evidence, it is clear that the subsidence in the area near the Dr. Poland photo has been less than 0.5 meters since 1975. Figure 2 shows an updated reference to the elevation changes at this location based on the June 2017 level run.

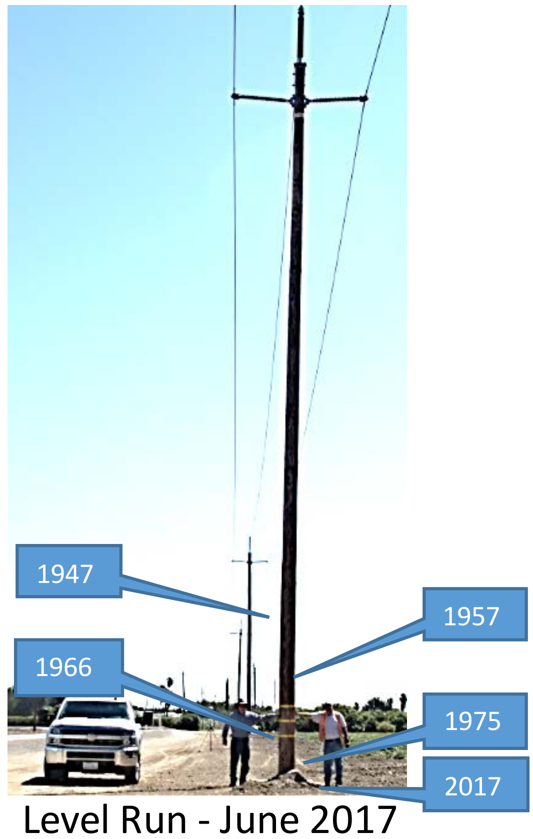

Figure 9. Recommended subsidence reference for Benchmark S 661 near Mendota, CA

CONCLUSION

This area clearly has had subsidence occurring over the years. This review was not intended to determine the expected rate of subsidence in the future, nor was it to explain the cause of the subsidence. The review was only an attempt to check the repeatability of existing data as well as estimate subsidence since the famous photo was taken.

There are two major findings of this review. First, based on the information provided and the authors' understanding of the information available, it is unreasonable to expect anyone could precisely determine the subsidence along the west side of the San Joaquin Valley in this general area. In other words, there is uncertainty in the data. Although there have been plenty of level runs in this area, there is no simple way to correlate them.

The second point is that the data indicates there may be a significant discrepancy in this area which may have shown subsidence in excess of 3.5 meters more than the actual subsidence. In addition, none of the data goes back further then 1943, although Dr. Poland is showing change in elevation back to 1925. There may be some local leveling that was done back in 1925, but again it would be hard to correlate that data with the NGS level lines. Therefore, although the Dr. Poland photo is startling, the review identified uncertainty in the magnitudes of subsidence presented. It is also clear that the subsidence has occurring after 1977 is negligible compared to the original photo.